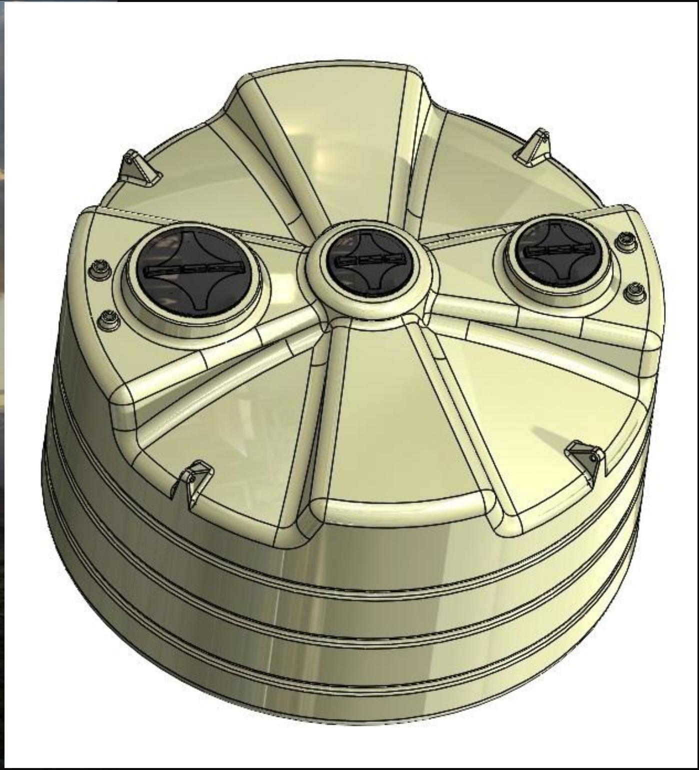
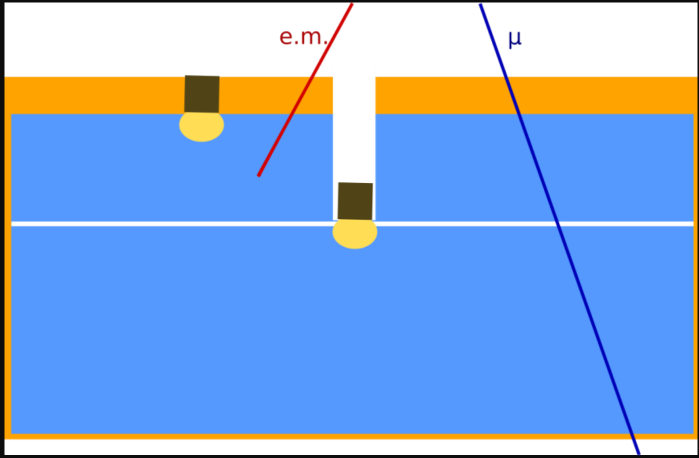


Probing the PeV Gamma-Ray Sky with PEPS (Probing Extreme PeVatron Sources)



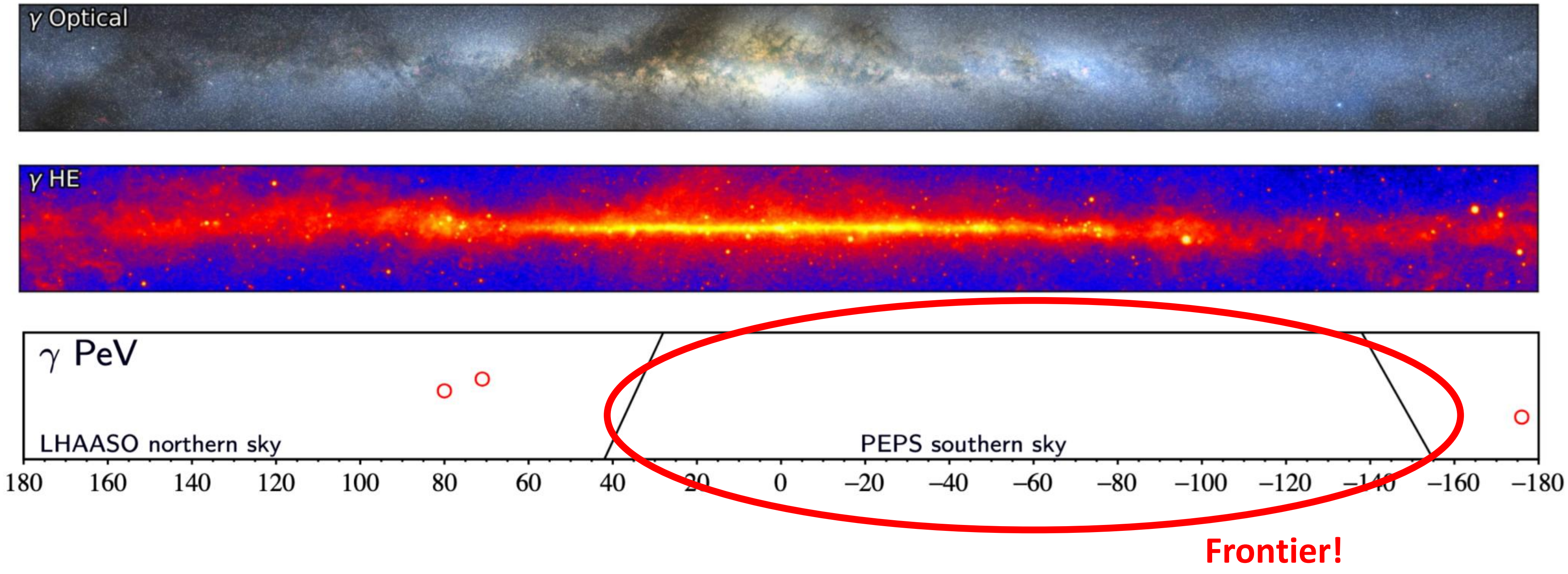
E. Kido[1,2] on behalf of the PEPS Collaboration

ICRR Univ. of Tokyo[1], ABBL RIKEN[2]

Outline

- Concept of the experiment and the performance simulations
- Prospects of physics cases
  - Expected event rate
  - Dark matter search and cosmic ray measurements
- Hardware developments
- Summary and prospects

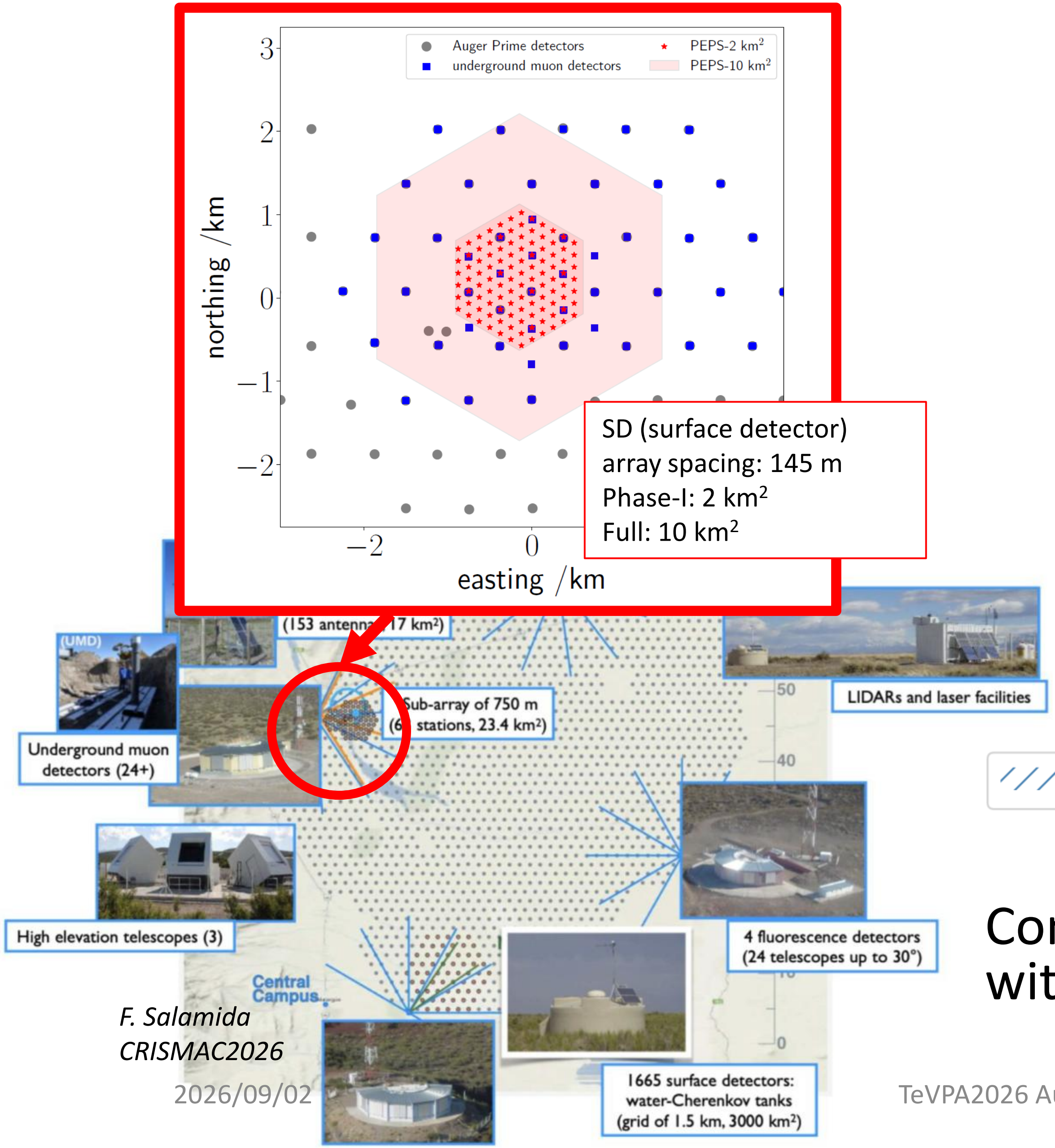
Explore the highest-energy gamma-rays from Galactic sources



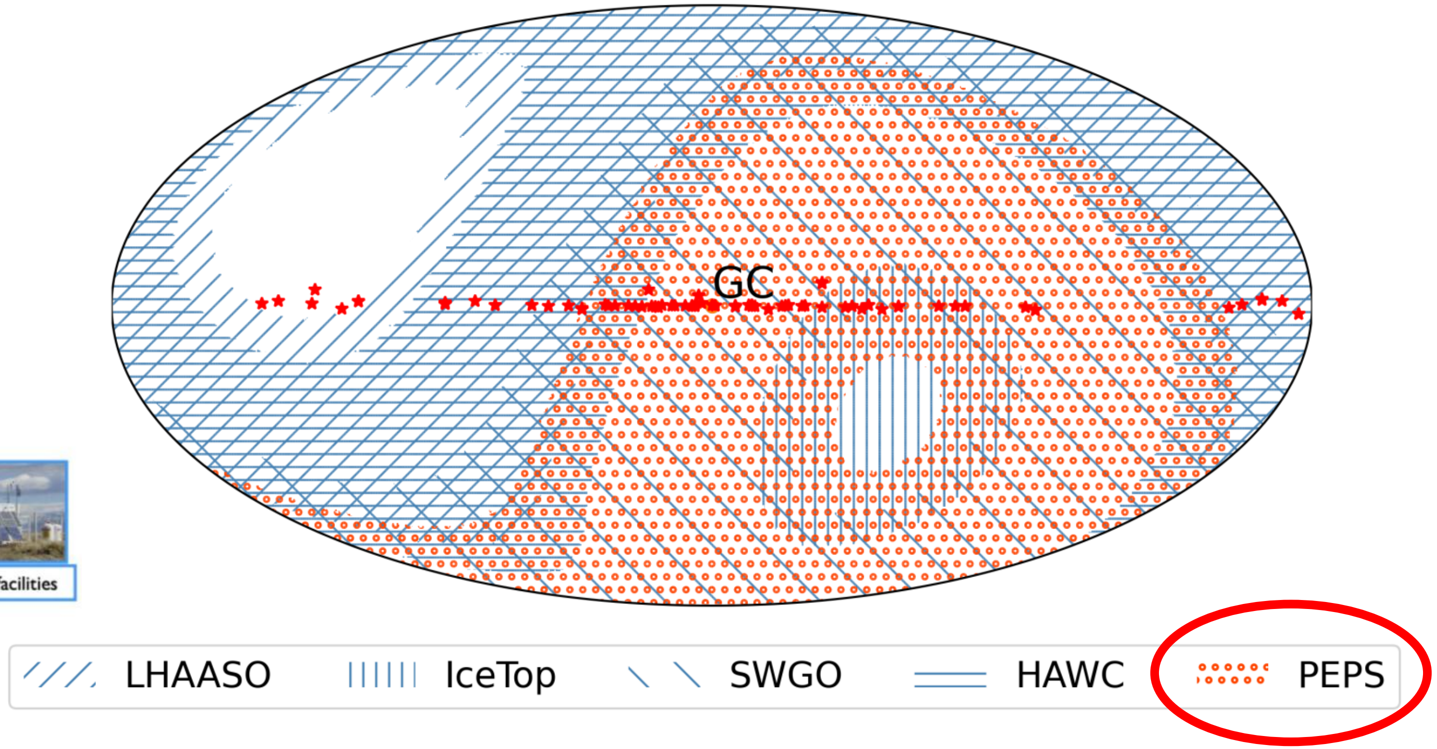
Explore the >2 PeV gamma-ray sky in the Southern Hemisphere

Pierre Auger Observatory site in the Southern hemisphere:
Malargue, Mendoza, Argentina

Observation site and the field of view

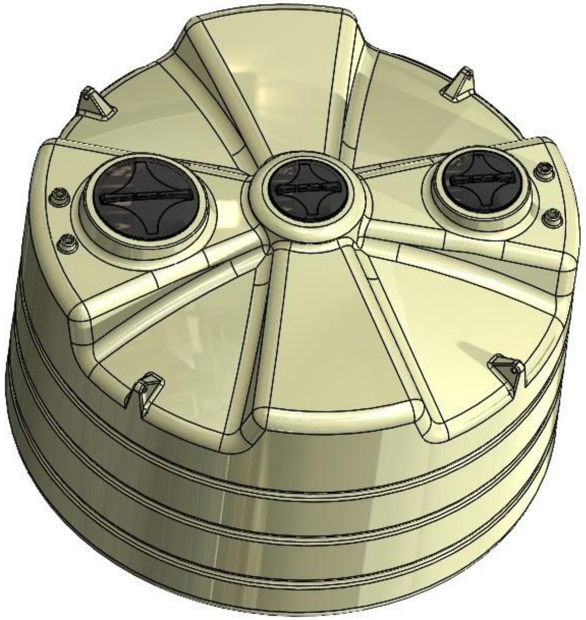


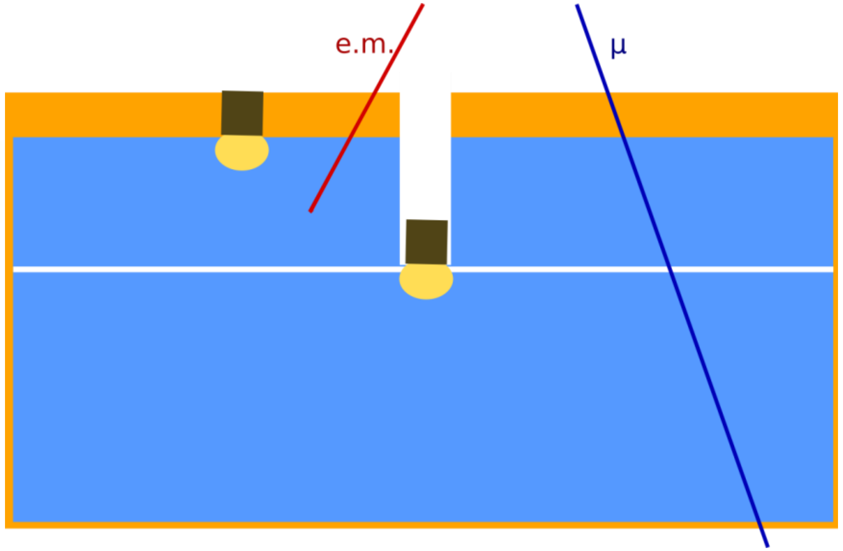
F. Salamida
CRISMAC2026



Complementary to Northern-Hemisphere experiments, with overlapping FoV in the Southern Hemisphere

Layered water Cherenkov detector (WCD) concept





- Layered WCD surface detector (SD)

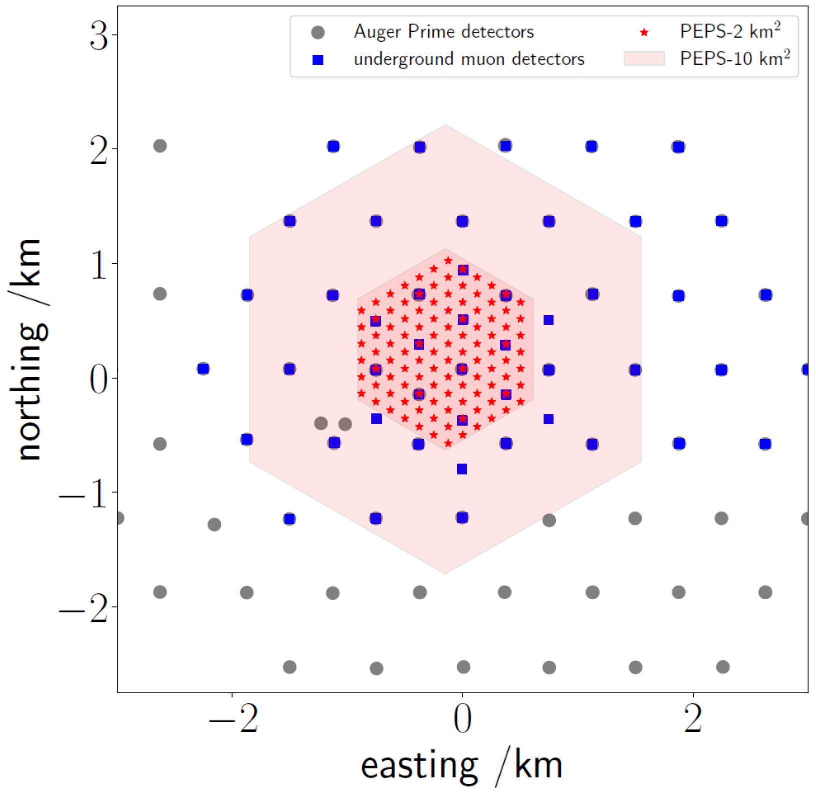
  A. Letessier-Selvon et al.,

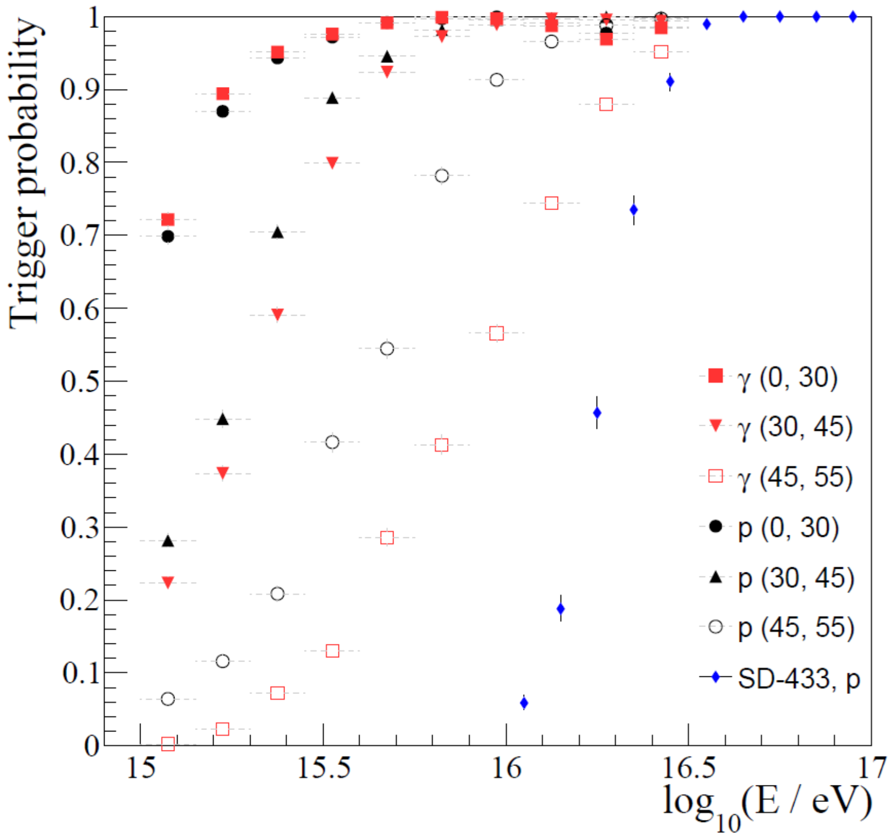
  NIM A767 (2014).
  - Diameter: 3.2 m*
  - Water depth: 50 cm (up), 80 cm (low)*
  - 2 PMTs: one per water volume
- Two layered WCDs have been operating at the Auger site since 2014.
- EM/muon discrimination using the different responses of the two layers

  → gamma-ray detection

*: studies are ongoing

Performance simulations: array design and trigger efficiency

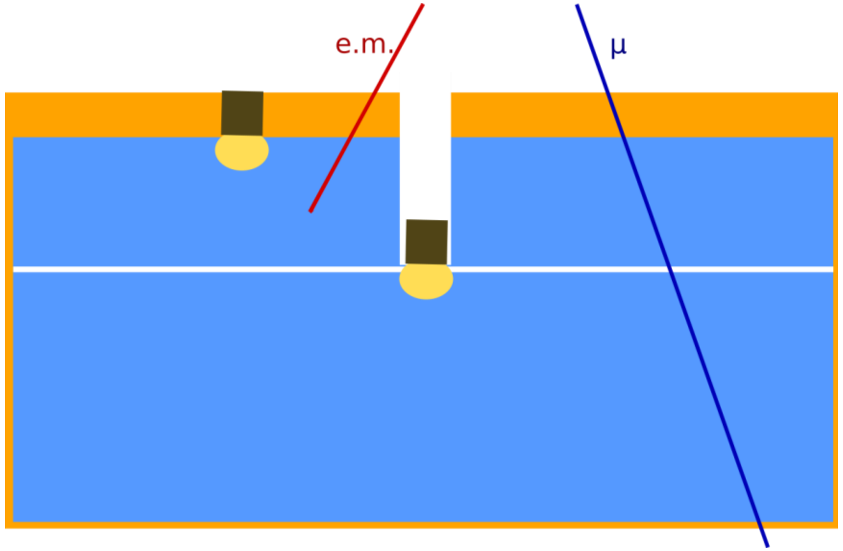


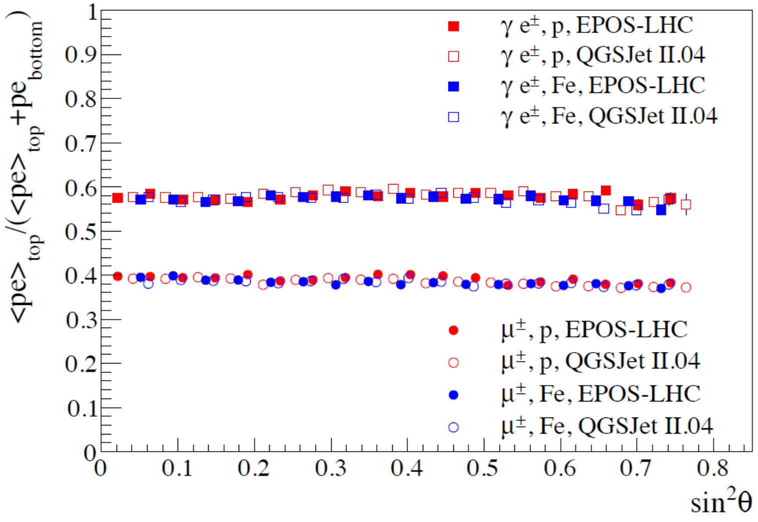


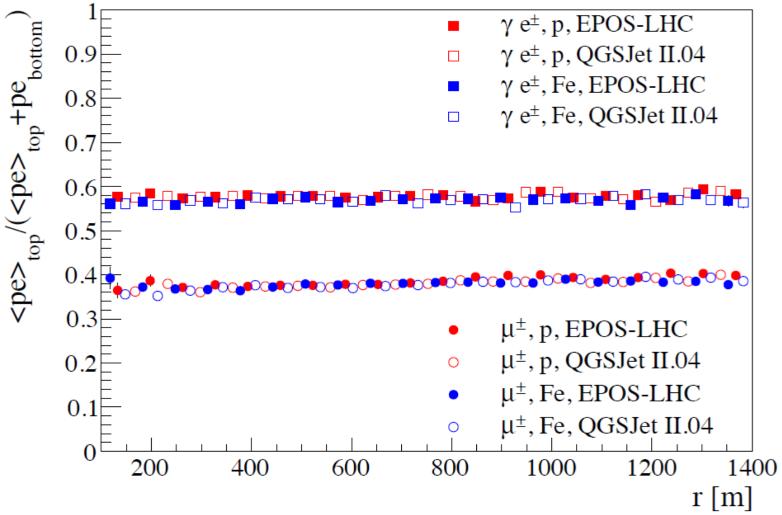
CORSIKA sim. w/ EPOS-LHC model
by N. Gonzalez and E. Santos

- Array spacing: 145 m
- High trigger efficiency for gamma rays **above 2 PeV**
- ～125 stations for a 2 km² array
- ～550 stations for a 10 km² array

EM/muon separation with a layered WCD







A. Letessier-Selvon et al., NIM A767 (2014).

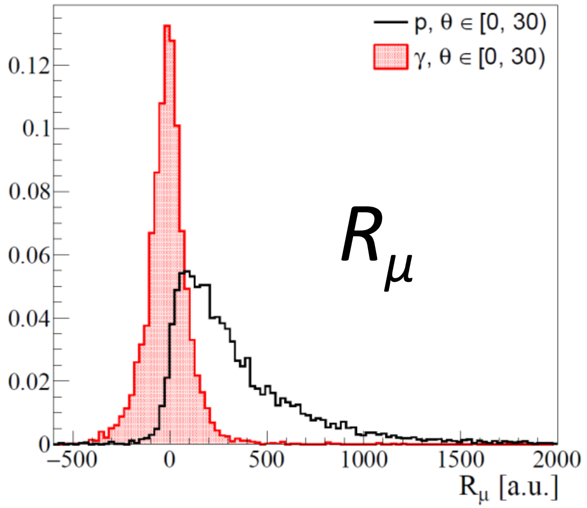
- Muon signal reconstruction with a layered WCD
- Different responses to shower components
  - EM: mainly absorbed in the upper layer
  - Muons: penetrate both layers
- Universality of the response matrix
  - *a* and *b* are nearly independent of shower properties
  - S_μ can be reconstructed event by event from the top/bottom signals

$$\begin{pmatrix} S_{\rm top} \\ S_{\rm bot} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\rm EM} \\ S_\mu \end{pmatrix}$$

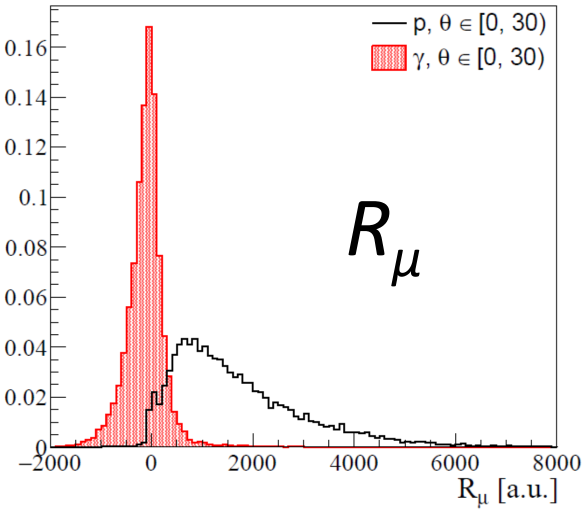
$$S_{\rm top}, S_{\rm bottom} \Longrightarrow S_{\rm EM}, S_\mu$$

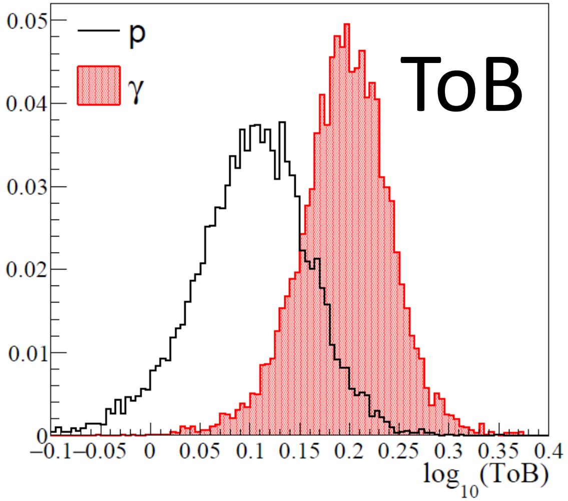
Performance simulations: gamma/proton discrimination

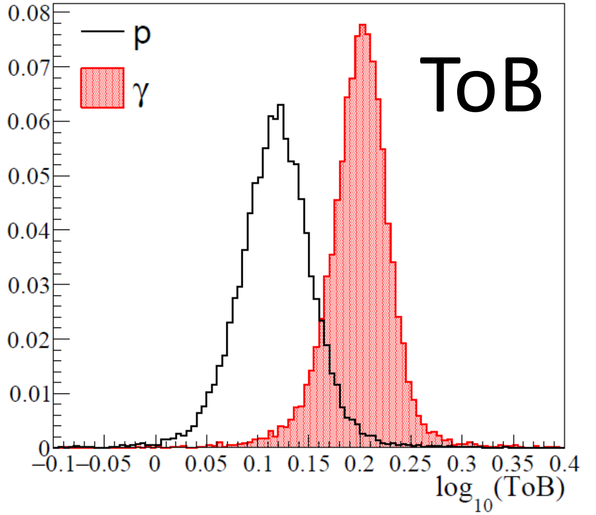
$\log_{10}(E/\mathrm{eV}) \in [15.5 - 16]$



$\log_{10}(E/\mathrm{eV}) \in [16 - 16.5]$







$$R_\mu = \frac{1}{N}\sum_{i}^{N} S_\mu \cdot r^{1.5}$$

$$\log_{10}(\mathrm{ToB}) = \log_{10}\left(\frac{1}{N}\sum_{i}^{N}\frac{S_{\mathrm{top}}}{S_{\mathrm{bottom}}}\right)$$

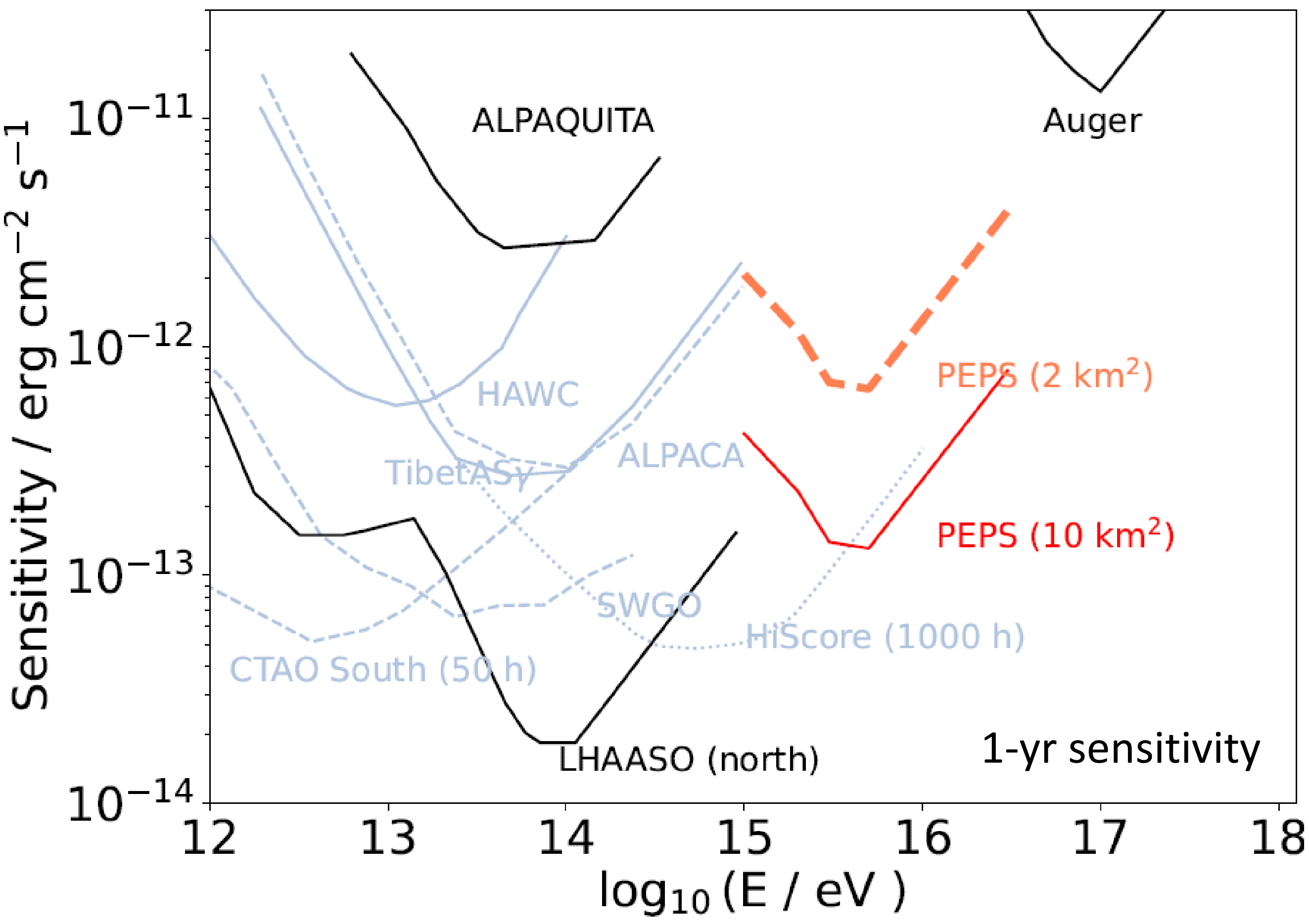
Two separation variables

- At 50% gamma efficiency, combination of the two separation variables →
  - Proton leakage decreases rapidly with energy
  - **< 5x10^{-3}** around 1 PeV
  - **< 10^{-4}** above 10 PeV
- The gamma/proton separation has not yet been optimized. **Neural-network**-based methods are under development.

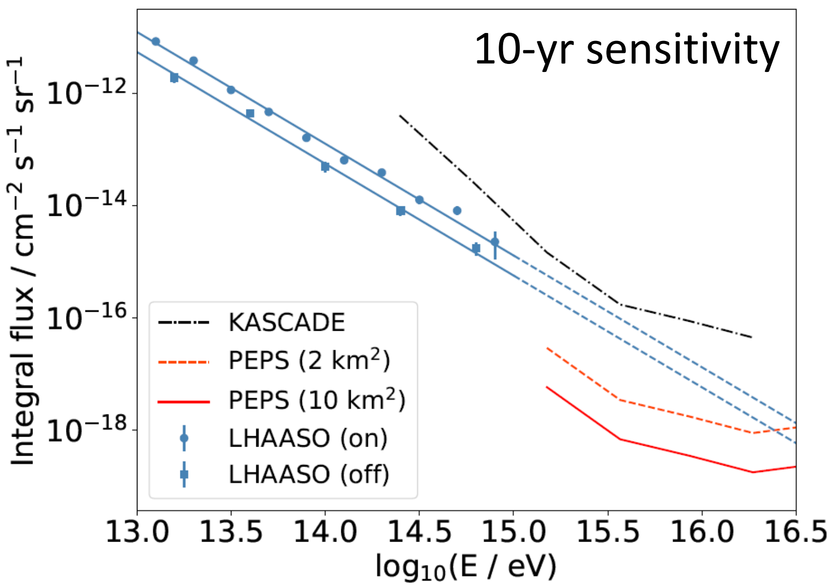
I. Maris and N. Gonzalez PoS(ICRC2023)718

PEPS sensitivity in the PeV γ-ray range

Point-source sensitivity

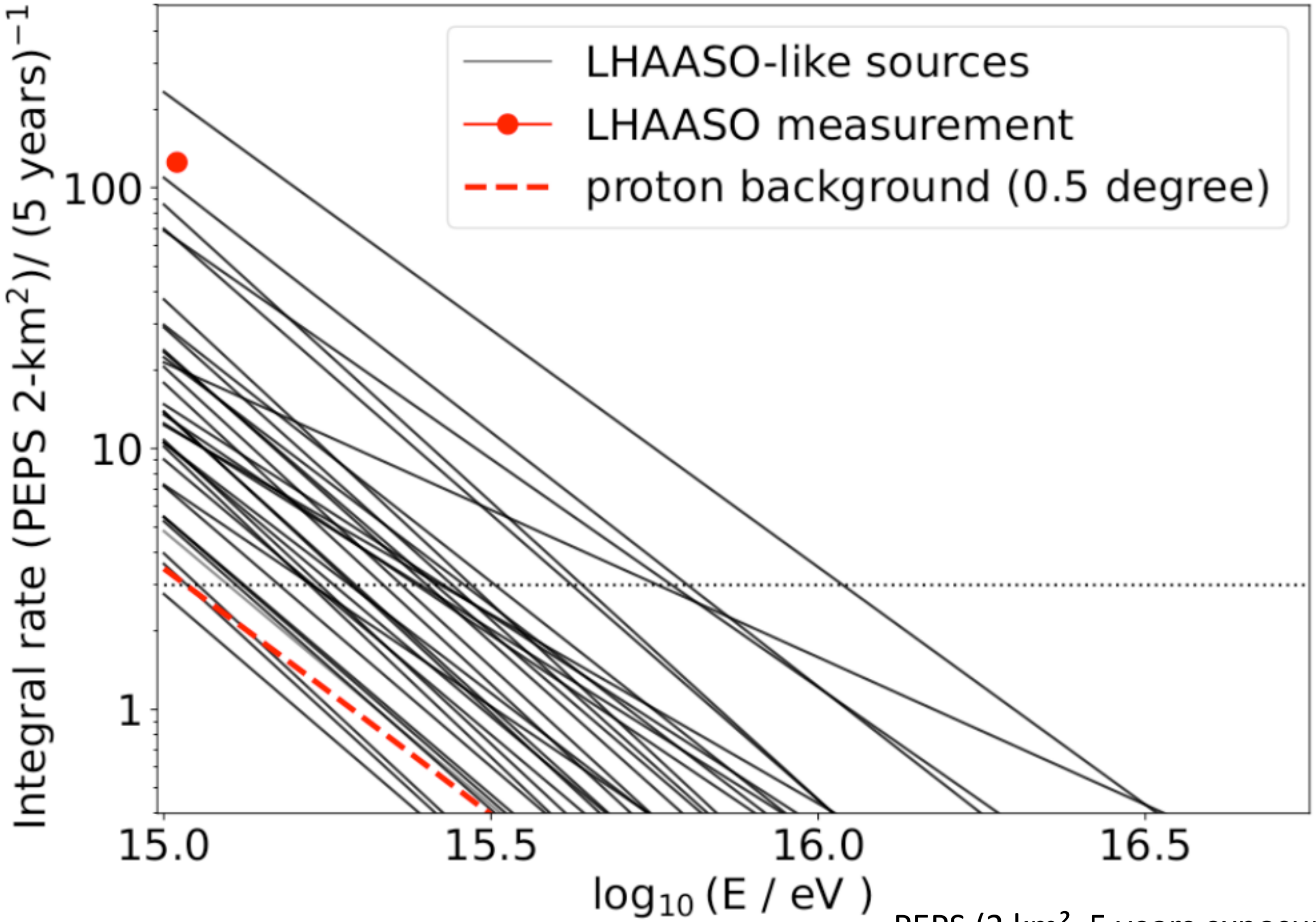


Diffuse-flux sensitivity



- Point-source sensitivity (1 yr):
  PEPS extends γ-ray measurements beyond ～1 PeV, where **current coverage is limited**.
- Diffuse-flux sensitivity (10 yr):
  PEPS will test whether diffuse flux extends to higher energies. **PEPS could probe the diffuse Galactic emission** beyond 1 PeV, even allowing for attenuation around 2 PeV.

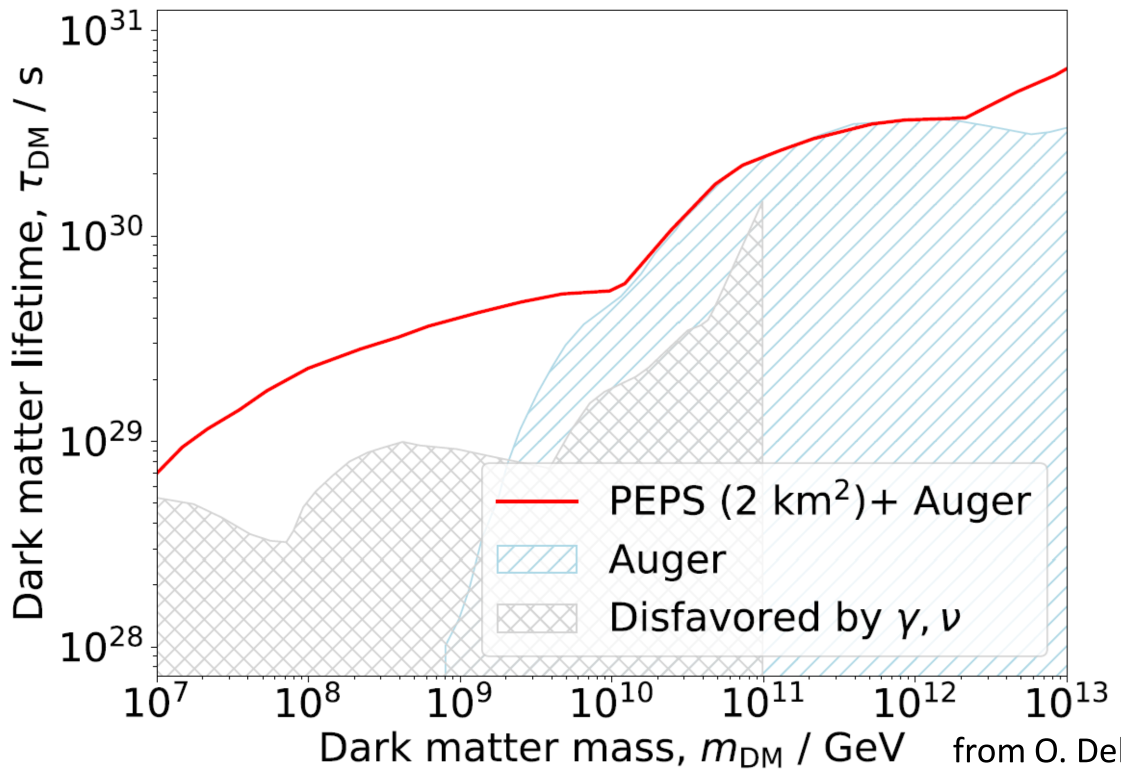
Expected event rate for PEPS



PEPS (2 km², 5 years exposure)
Proton background efficiency: 3x10^{-4}

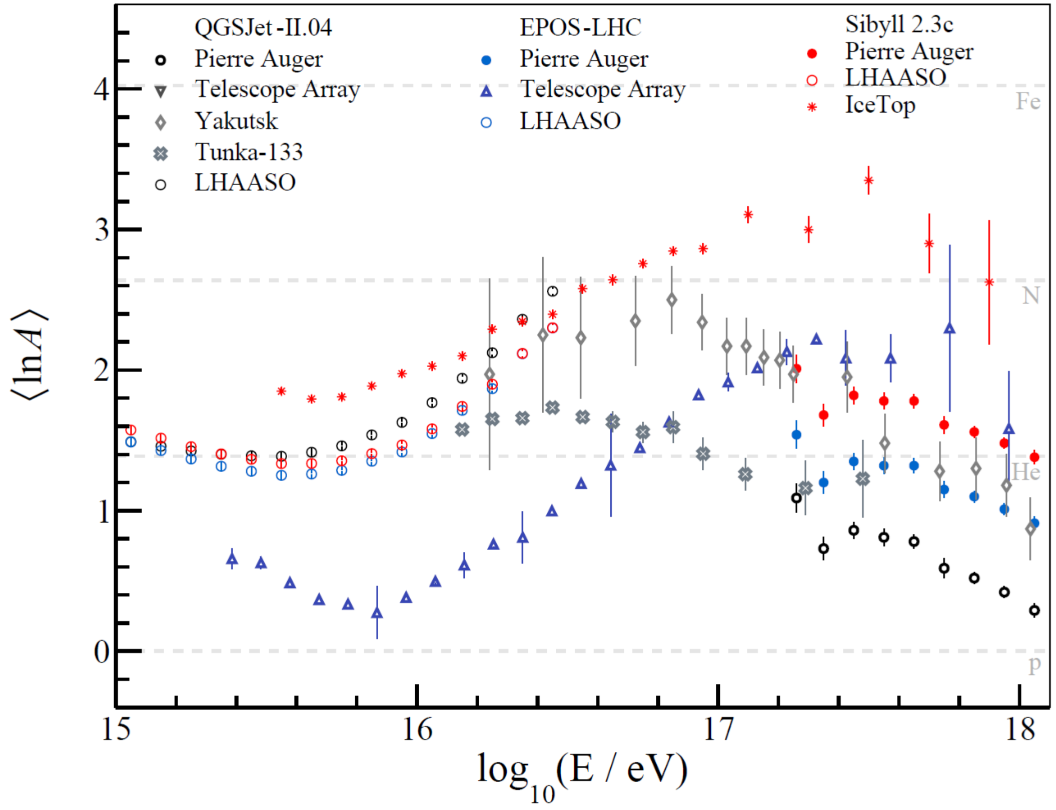
- Highest-energy LHAASO event: 3.73 ± 0.41 PeV from Cygnus X-3.
- “LHAASO-like sources”: benchmark sources with fluxes/spectral shapes similar to bright sources measured by LHAASO
- Simple extrapolation to higher energies, assuming no attenuation and no intrinsic cutoff
- A 2 km² PEPS array **can collect measurable samples** from bright LHAASO-like sources over several years.

Dark matter search and cosmic ray measurements



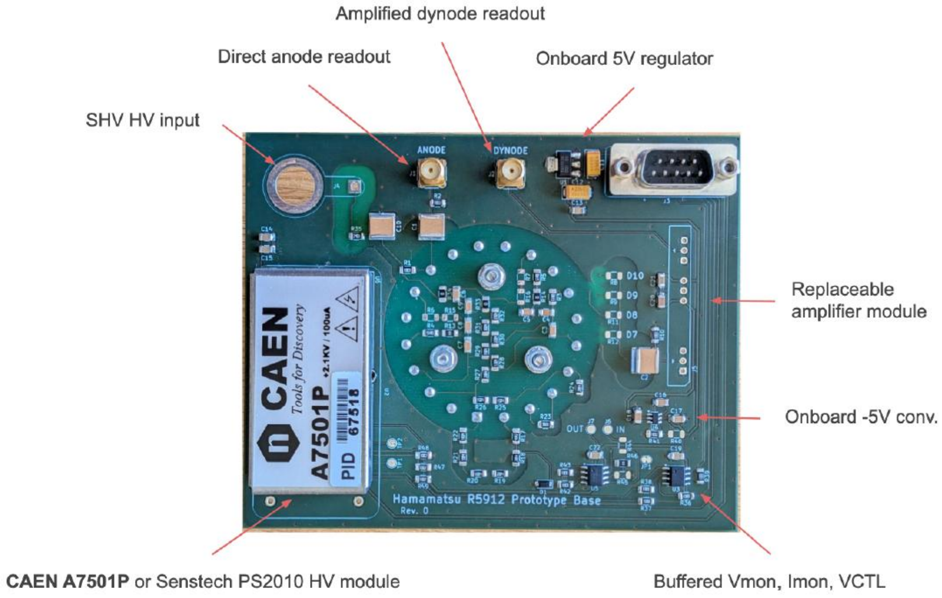
from O. Deligny

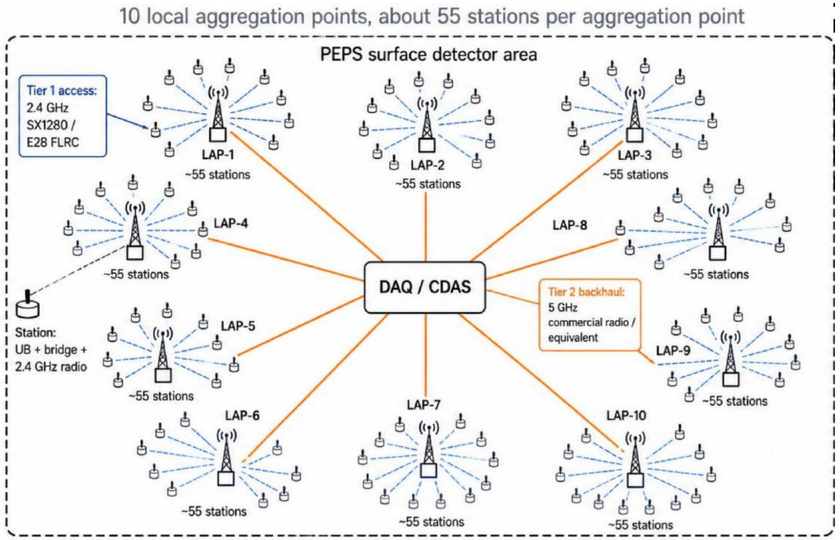
UHE gamma rays from super-heavy dark-matter decay
→ constraints on the dark-matter lifetime



Cosmic-ray composition measurements with layered WCDs
→ comparison with existing measurements

Hardware developments





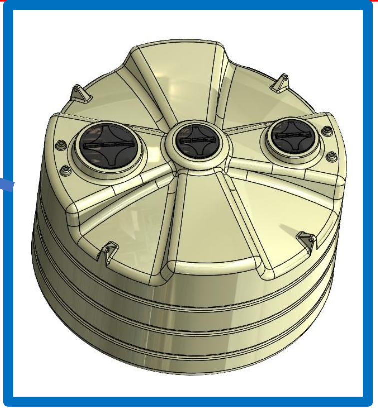
Topology of wireless communication for the data acquisition

Blue: 2.4 GHz wi-fi

Orange: 5 GHz wireless comm.

- FZU Prague and ULB Brussels
- Hamamatsu R5912 PMTs are being tested
  - Single-photoelectron response
  - Linearity
  - Afterpulse
  - Dark rate
- PMT base
  - Adjustment for the PMT and front-end electronics
- Reuse existing Auger equipment
  - Solar panels
  - Unified boards
- Wireless communication
  - The proposed wireless communication does not overlap with the frequencies currently used by the Auger DAQ.

Hardware development at the Akeno Observatory



- A PEPS station will be constructed at the Akeno Observatory.
- Nine ALPACA SDs are also planned for installation on the rooftop.
- Coincident air-shower events will be measured with the PEPS and ALPACA detectors.

Summary and prospects

- PEPS: Probing Extreme PeVatron Sources
- Concept: a dense array of layered water-Cherenkov detectors

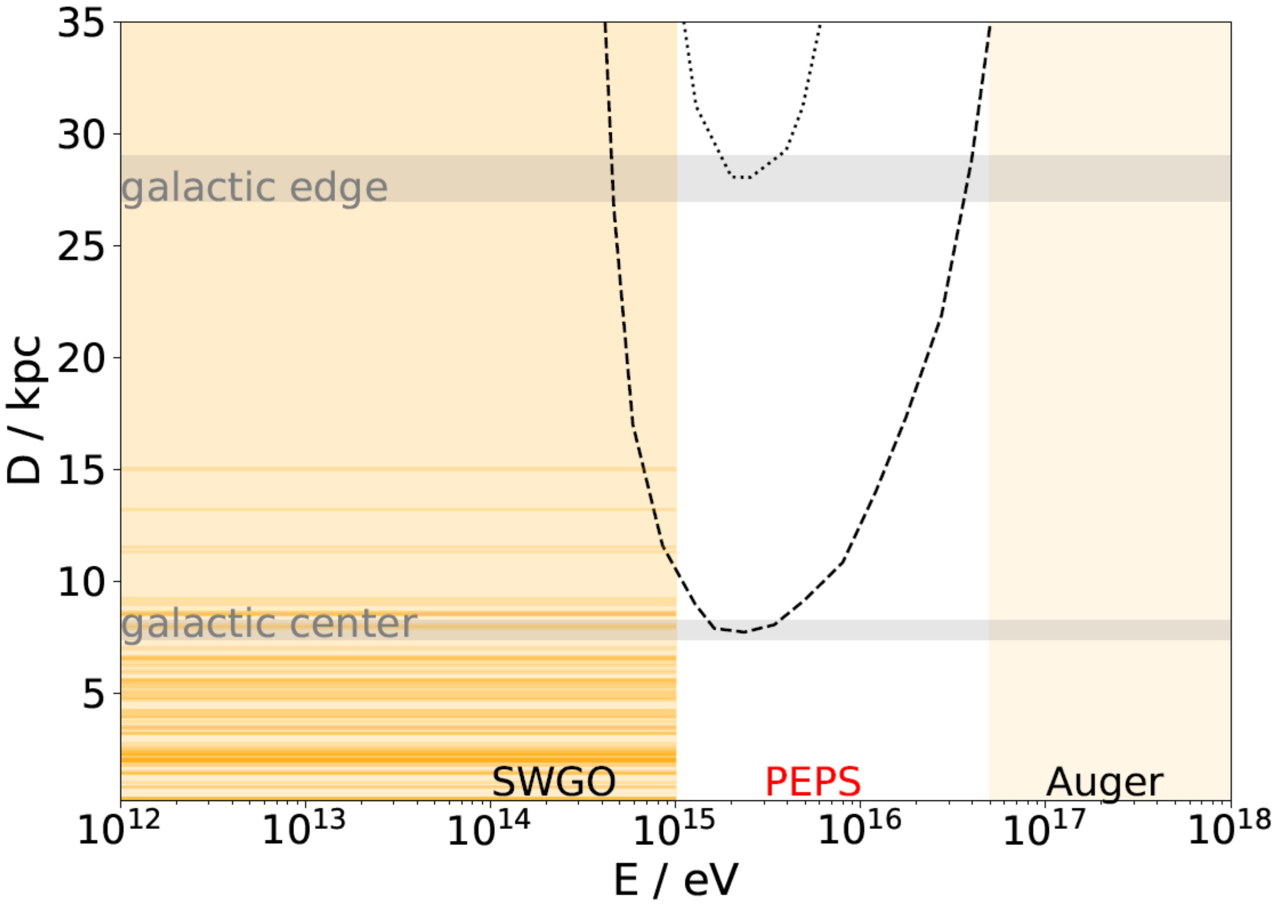
  → a **large-area gamma-ray observatory** in the Southern Hemisphere, targeting energies above **2 PeV**
- Hardware developments are ongoing.
- An 8-station prototype array (PEPSino) is planned for deployment in 2026–2027.

PEPS

Interested? Join us!

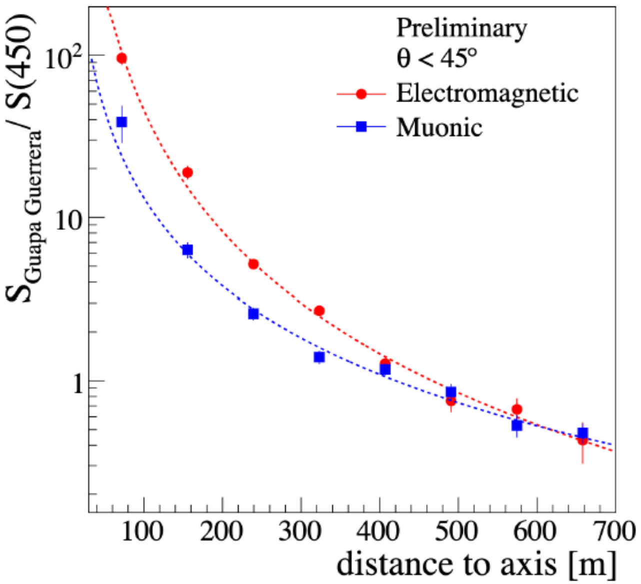
Probing Extreme PeVatron Sources (PEPS)

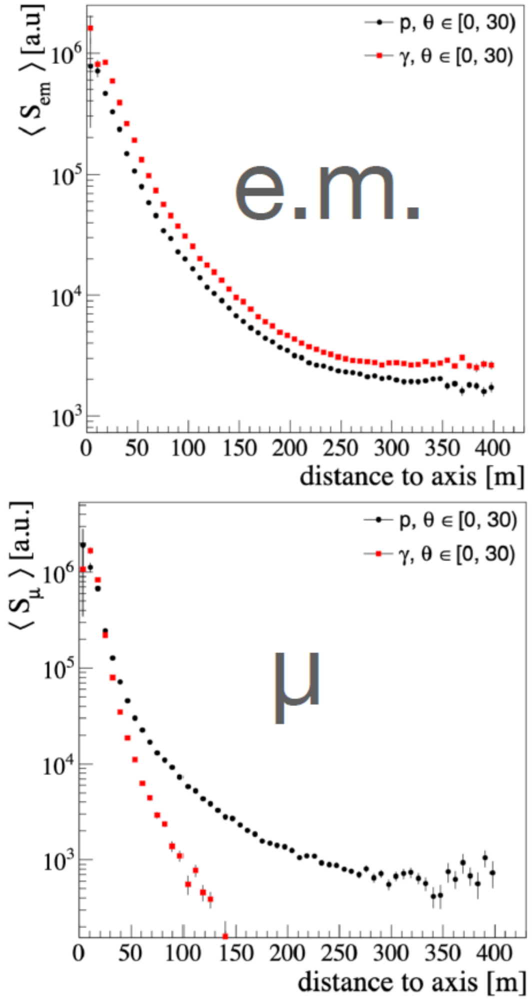
Absorption of photons

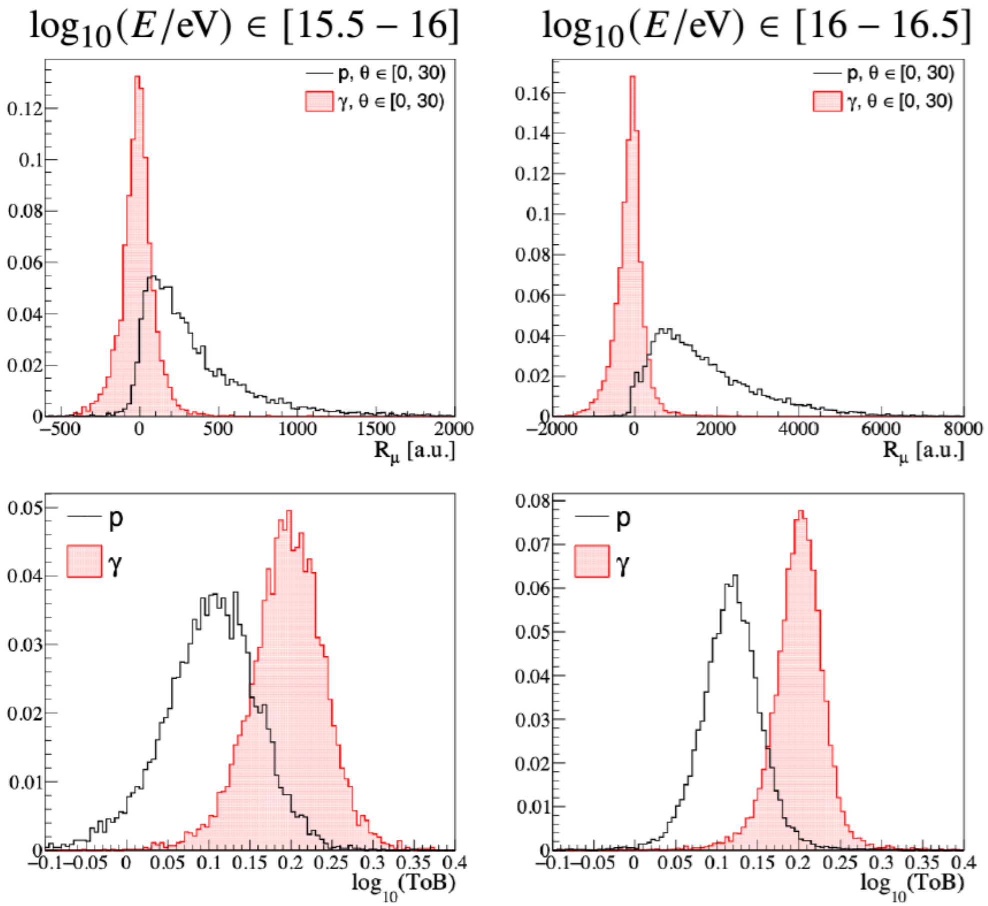


Gamma-hadron separation

Data from prototypes
(A. Letessier-Selvon et al., NIM A767 (2014))







Separation variables = S_{top}/S_{Bottom} + LDF

Separation power @ 50% signal efficiency

10^{-3} above 2 PeV

10^{-4} above 10 PeV

Not optimized, expected improvements with NN and UMD measurements

$$\log_{10}(\text{ToB}) = \log_{10}\left(\frac{1}{N}\sum_{i}^{N}\frac{S_{\text{top}}}{S_{\text{bottom}}}\right) \qquad R_{\mu} = \frac{1}{N}\sum_{i}^{N} S_{\mu} \cdot r^{1.5}$$

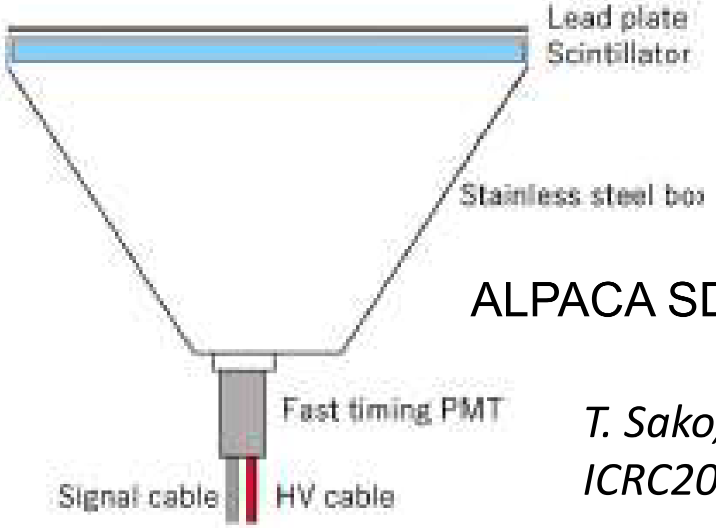
ALPACA SD array on the rooftop (plan)

http://www-ta.icrr.u-tokyo.ac.jp/ta_public/kyoten2025/posts/post.html

- 9 SDs at the rooftop
- Spacing～15 m
- *E* > ～100 PeV energy events
- Observation site:

  altitude: 900 m

  Latitude 35° 47’ N, Longtude 138° 30’ E



ALPACA SD

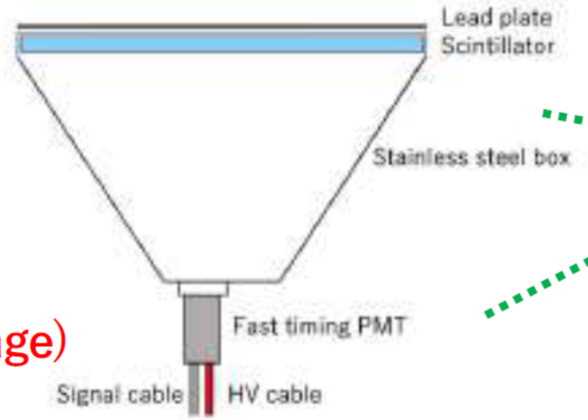
T. Sako, ICRC2025

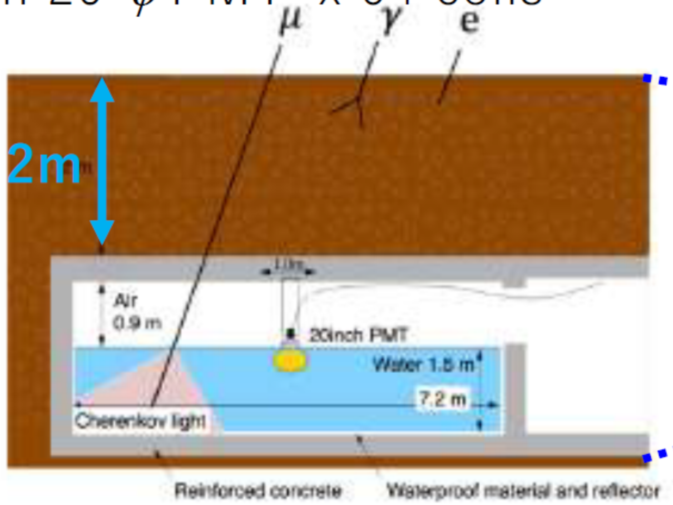
T. Sako,
ICRC2025

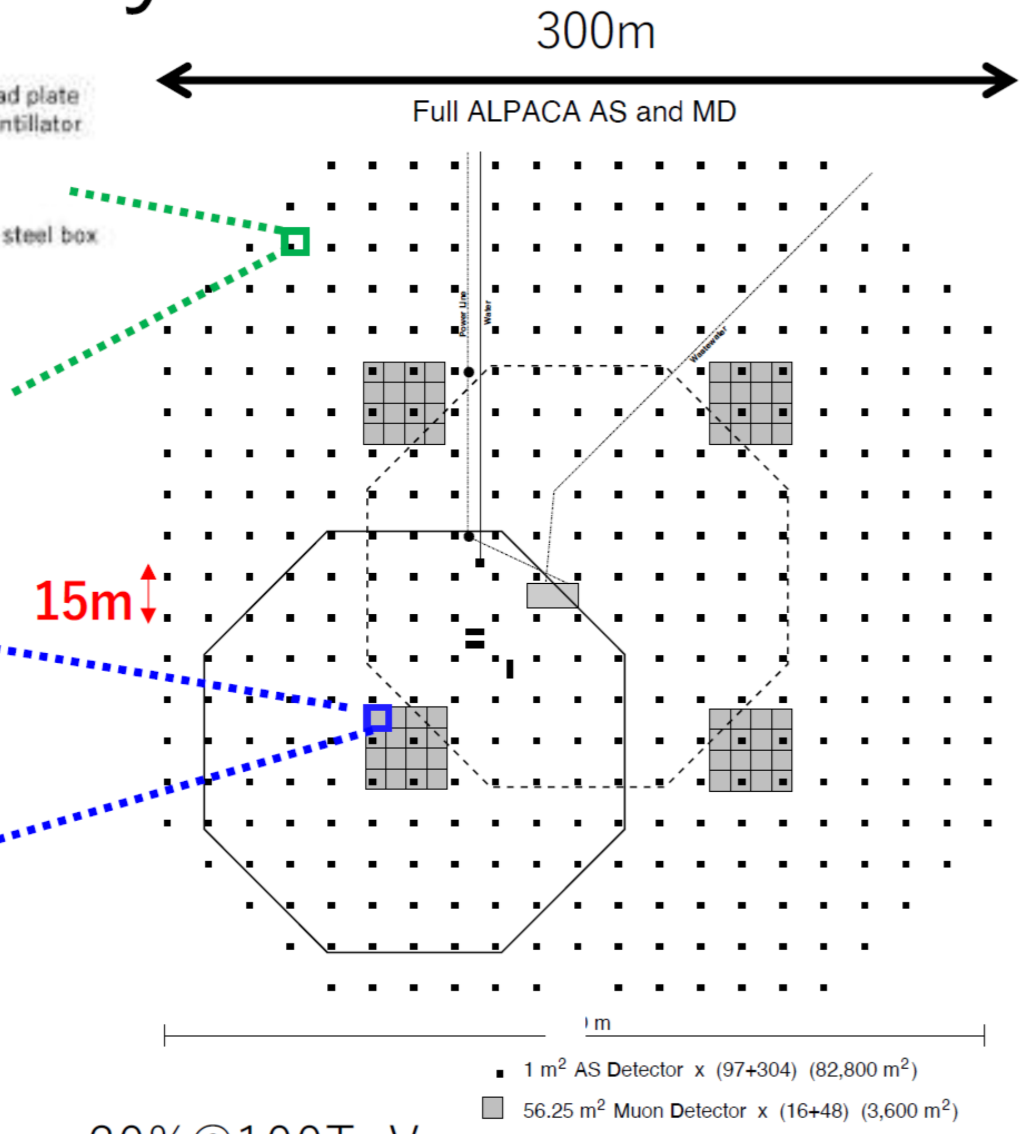
ALPACA Array

1. **Array coverage 82,800m²**
   = 401 x 1m² plastic scintillators

2. **Underground water Cherenkov muon detector (MD) 3600m²**
   Soil over 2m (~16X_0) (4.3% coverage)
   = 58m² with 20”ϕ PMT x 64 cells







- ✓ Cosmic-ray BG rejection power >99.9% @100TeV.
- ✓ Angular resolution ~0.2° @100TeV, Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

PMT gain and linearity measurements